

Requirements for Science Data Processing for Constellations of NanoSats

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Overview

The evolution of scientific spacecraft missions to constellations of nanosats will severely strain the capabilities of traditional legacy science data processing systems. Although ongoing advances in technology will allow for implementation of systems that will handle five to ten times the current processing load, the life-cycle cost to operate such systems will be prohibitive. We seek solutions that allow for less than linear scaling in cost-to-operate.

A series of recommendations and approaches are presented. The most important of these is to become involved early in the planning phases of constellations, to ensure that the immensity of the problem of science data processing is not overlooked. Short-term band-aid class solutions abound. However, a new paradigm of science data processing for constellations consisting of hundreds of nanosats must be derived.

The lack of hard requirements for science data processing from the many constellation projects examined is troublesome. It leads to the assumption that constellation projects are assuming that backend science data processing will scale, and that costs can be contained. This assumption is not at all obvious.

Introduction

This report discusses the requirements for Science Data Processing for constellations of nanosats. The primary problem to be addressed is control of development, deployment, and operational costs for multiple spacecraft. As the paradigm for science and earth observing satellites shifts from large single spacecraft missions to those involving large numbers of smaller, inexpensive spacecraft, it is essential to control costs. The challenge is to contain the cost to process science data from 100 spacecraft; costs cannot be allowed to rise to 100 times that of a single spacecraft.

Scope

This report only discusses the area of the processing of science data from constellations of spacecraft. It does not discuss science or mission planning, or on-orbit operations for constellations.

This report presents a snapshot of the possible requirements on science data processing for constellations. This is an ongoing project, and this report will be updated periodically as operational experience is gained with constellations.

The CMWG

The Constellation Management Working Group (CMWG) was inaugurated by NASA-GSFC, code 580, the Information Systems Center in 1999. The key points of contact for the CMWG are Mr. Peter Hughes, and Mr. Gary Meyers. The central repository of information for the CMWG is the website implemented by QSS Group, <http://CMWG.GSFC.NASA.GOV>.

The charter of the CMWG is to define the problems and challenges of formulation, implementation, and operation of a constellation of spacecraft and to recommend potential approaches to solving them.

There are assumptions in the CMWG study. One of these is that current mission system capabilities and operation methods are inadequate for constellation missions. Another is that the majority of near-term constellation missions will implement homogeneous spacecraft. This is thought to simplify many issues.

All four of the reference missions specify the same complement of instruments. In the near and medium term, homogeneous instrument sets are the norm. Although the instrument set will start out homogeneous, they will degenerate into heterogeneous in time, as equipment drifts, degrades, and fails. We can also consider the case of later spacecraft in the constellation having different instruments, based on experience with the early flights, and technology evolution.

Constraints on the CMWG study include that total mission system development and operations costs for a constellation mission should NOT be linearly proportional in cost per spacecraft to that of current single spacecraft missions. It is highly desirable for the operations costs for constellations to be near the costs of current missions.

The scope of the CMWG includes all data systems and operations activities for spacecraft constellation missions including:

- Systems engineering
- Ground segment and space segment to the extent that it affects operations manpower
- Spacecraft integration and test Prelaunch operations preparation
- Launch and early orbit
- Routine operations including spacecraft and payload health and safety, command and control, data acquisition, and the management of the resulting engineering and science data.
- Science data processing levels 0 - 4
- Sustaining engineering

Thus, the scope of the CMWG is much larger than the scope of this report.

Target Products and Results of the CMWG include a prioritized list of problems and challenges and recommended solutions for the formulation, implementation, and operation of spacecraft constellations. This list identifies target or prospective missions, need dates (near 0 - 3 years, mid 3 - 6 years, and far-term 7+ years) and the criticality of the need.

Near/mid-term constellations

Although there are commercial constellations deployed (Iridium, GlobalStar, and others), these are mostly communications constellations, and do not return science data. The CMWG defined four near to mid-term NASA constellation missions that would drive requirements. The missions considered by the CMWG are discussed below.

The Nanosat Constellation Trailblazer Mission

These are three very small satellites, called the Nanosat Constellation Trailblazer mission, selected as NASA's latest New Millennium mission. The mission will validate methods of operating several spacecraft as a system, and test eight technologies in the space environment near the boundary of Earth's protective magnetic field, or magnetosphere. Each Trailblazer spacecraft will be a small octagon 16 inches across and 8 inches high, and each will have booms and antennas that will extend after launch. The mission will cost \$28 million and will be launched in 2003 as a secondary payload on an expendable launch vehicle.

Results from the Trailblazer mission will be used to design future missions using constellations of lightweight (about 44 pounds), highly miniaturized autonomous spacecraft. One proposed constellation of up to 100 spacecraft positioned around the Earth will monitor the effects of solar activity that can affect spacecraft, electrical power and communications systems. Others will study global precipitation and the atmospheres of other planets.

The Nanosat Constellation Trailblazer is the fifth in NASA's New Millennium program, which tests technology for future space and Earth science missions. The program's goal is to dramatically reduce the weight, size and costs of missions while increasing their science capabilities.

The impact of 3-5 very small satellites on science data processing is minimal, but the current project is just a trailblazer for larger constellations, perhaps of 100 or more members. The scalability of current science data processing systems to 100 input data streams is unknown, but highly unlikely, without prohibitive cost.

Constellation-X

The Constellation-X Mission will consist of a group of X-ray telescopes in space, working in unison to improve the view of the X-ray universe by a hundred-fold. The mission is a key element in NASA's Structure and Evolution of the Universe theme,

dedicated to unlocking the mysteries of black holes, galaxy formation and the Universe's still undetected matter. The mission planning is in an early stage, and no specifics could be found on data processing requirements. As a placeholder, the science data processing will be assumed to be an extrapolation of that of "typical" X-ray, high energy missions.

ST-5

The Magnetotail constellation mission is also known as DRACO - Dynamics, Reconnection, and configuration observatory. The following is abstracted from the Report of the NASA Magnetospheric Constellation V Science and Technology Definition Team:

"Magnetotail Constellation DRACO is the Solar Terrestrial Probe (STP) mission designed to resolve controversies concerning the complex dynamics of the magnetotail. To achieve observational closure with theory, we must distinguish spatial structures from temporal variations throughout the magnetotail. This requires a large number of small yet highly capable spacecraft, creating a station network capable of resolving 2 RE scales at 10 sec time resolution, over a 15 x 30 RE domain." Neither current single spacecraft, nor even tight groups of spacecraft, are sufficient to resolve these theoretical controversies of the magnetotail.

"DRACO will provide the first global time-evolving maps of fields and flows in this important region. Using recently available technologies, the magnetotail can now be reached with a swarm of small spacecraft. Such a swarm is novel in its ability to simultaneously resolve magnetic fields and flows throughout large volumes of the magnetotail. DRACO is designed to provide the groundbreaking data needed to understand how the magnetotail really functions."

Again, the data processing requirements from 5 spacecraft will not necessarily overwhelm current systems. The key is to contain operations costs.

MMS - Magnetospheric MultiScale (Constellation)

MMS is approved as part of solar terrestrial probes (STP) program. It is scheduled to launch in 2006/2007. The mission is cost-capped at \$120 M for phases C/D

There will be 5 spacecraft, each spin stabilized, formation flying in a double tetrahedron. All launch at same time from expendable launch vehicle (Delta class). Intersatellite communications will be used for ranging and for alarms to trigger high data rate recording mode. The orbits vary by mission phase:

- Phase I - 1.2 x 12 RE, I = 10 degrees, period = 24 hours
- Phase II - 1.2 x 30 RE, I = 10 degrees, period = 3.6 days
- Phase III - 8 x 80 RE, I = TBD, period = 14 days
- Phase IV - 10 x 50 RE, I = 90 degrees, period = 5.2 days

The downlink data rate is 1.5 Mbps, with a data volume of 2Gbits/day. Data dumps during Phases II-IV will occur at 2.2 Mbps when the spacecraft is closer than 29 RE.

Routine Operations will be conducted for 2 years nominal, with on-board attitude determination. The spacecraft will be supported sequentially by ground stations, with USN support (command, telemetry, tracking, science data dumps) during Phases I and II; tracking support only during Phases III and IV. DSN support will be used during Phases III and IV (command, telemetry, tracking, and science data dumps).

Science Processing will consist of LZP. Beyond this, the science data processing is not specified.

Additional Constellation projects

In addition to the missions being considered by the CMWG, the following additional constellation projects were examined for requirements for science data processing:

The University NanoSat Program

Utah State University, University of Washington, and Virginia Polytechnic Institute are designing and developing a system of three 10-kg spacecraft to investigate satellite coordination and management technologies and distributed ionospheric measurements. The three will coordinate on satellite design, formation flying, management mission development, and science instruments and mission. An Internet-based operations center will be designed to enable each university to control its satellite from its own remote location.

One objective of the program is the understanding of ionospheric density structures that can impose large amplitude and phase fluctuations on radio waves passing through the ionosphere. The constellation provides a unique opportunity to answer questions about ionospheric disturbances that can not be addressed any other way. A single satellite can only provide very limited information on the dimensions and evolutionary time scales of the ionospheric disturbances it flies through because a full orbit (90 minutes) must occur between the next observation. In general the situation is even worse than this because only truly zero inclination equatorial satellites have a good possibility of measuring the same region twice due to the co-rotation of the ionosphere with the Earth. This science investigation contributes to the TechSat 21 basic research mission of investigating global ionospheric effects which affect the performance of space based radars. It also addresses broader Air Force interests in ionospheric effects on navigation and communication links.

The nanosat constellation will be used to make the first global multi-satellite electron density measurements in the ionosphere. We also propose to make the first global multi-baseline RF-scintillation measurements of the ionosphere. The scintillation of GPS signals using receivers on each spacecraft will provide information about the scale sizes of disturbances between the nanosatellite constellation and the GPS transmitter.

One of two possible instruments will be deployed on each of the satellites in the constellation, either a plasma frequency probe from which an absolute electron density can be determined or an electron saturation current probe which can measure relative electron density variations. The instrument to be selected will be based on the resources available on the nanosat but in general these instruments will be small, low-power, and have low impact on their host satellites.

The scintillation measurements will be extracted from the GPS receivers that are part of the orbit determination system on the nanosats. The 1575 MHz signal from the GPS satellites originate at 20,000 km over the Earth and must travel through the ionosphere, line of site, to the location of the nanosats at 360 km altitude. The signal will encounter regions of disturbed ionospheric plasma which will slightly increase or decrease the signal strength at the receivers. The size of these disturbed regions can be estimated by comparing signals measured over closely related propagation paths, such as between two nanosats.

The basic satellite design is configured for released from a Shuttle Hitchhiker canister. The structure is hexagonal with an approximate 18 in. width and a 5 in. height. This configuration can be modified as needed to meet the specific launch environment conditions. The power regulation electronics will leverage high quality commercial NiCd batteries which have been developed commercially for portable laptop computers.

Ground Operations via Internet: The USU ground station will be used for ION-F, and another ground station, most likely at VT, will be developed. In order to successfully coordinate the three satellites, an Internet based ground station will be developed. This will allow coordination of experiments by the different universities as well as individual satellite control and data dissemination. VT is also investigating use of the GlobalStar LEO constellation for satellite telemetry, tracking and commanding of the satellite using commercial communications technology.

Commercial remote-sensing constellations

A number of commercial constellations have been deployed. These deployed systems address the voice, broadband data, messaging, navigation, and remote sensing markets. This report focuses only on the remote sensing constellations.

OrbView

Orbital Imaging (<http://www.orbimage.com/main/main.html>)has two remote-sensing satellites onorbit and are to launch another two. OrbView-1 was successfully launched on April 3, 1995. The satellite provides daily severe weather images, global lightning information and atmospheric monitoring to improve long-term weather forecasts. OrbView-2 was successfully on August 1, 1997 by OSC's Pegasus rocket. OrbView-2 offers broad-area multispectral imagery of both land and ocean regions. OrbView-3 is scheduled for launch in 2000. Satellite construction is underway by Orbital's Space Systems Group at its McLean, VA facility. OrbView-3 will offer one-

meter panchromatic and four-meter multispectral digital imagery. OrbView-4 is scheduled for launch in 2000. Satellite development is underway by Orbital's Space Systems Group in Germantown, MD. OrbView-4 will offer one-meter panchromatic, four-meter multispectral, and hyperspectral digital imagery.

RocSat-3

The Taiwanese government has apparently also announced that Rocsat-3 will be a constellation of six satellites for remote sensing. No further details are available.

COSMO/SkyMed

COSMO (Constellation of small Satellites for Mediterranean basin Observation) is a program conceived and defined by Alenia Aerospazio - Finmeccanica S.p.A. to promote the use of satellite remote sensing. The project will predominantly provide dedicated services to the communities living around the Mediterranean Sea. The COSMO program also integrates the Italian SkyMed mission, conceived by Fiar and Officine Galileo. COSMO/SkyMed is the first and only constellation implementing both optical and radar satellites in optimized orbits, capable of fully meeting the challenging requirements for advanced applications dedicated to the management and control of Mediterranean basin resources.

The technical features of the COSMO/SkyMed satellite system are particularly tailored for near real time applications. Urban monitoring and civil work are made possible by the high frequency revisiting time combined with day-night - all weather operation. High ground geometrical resolution and stereo capabilities will allow an almost permanent control of the urban and rural areas. Cosmo/SkyMed high resolution images (2.5 m in the optical/panchromatic band and 3 m with the SAR sensor) will facilitate making new maps and updating older ones. The in-track stereo capability of the optical high resolution camera can be used for digital elevation maps.

The day-night and all weather observation capabilities of the SAR constellation will make it possible to implement new forms of control from space of violations of international codes and/or infringements of national laws. The constellation's observation capabilities in the optical and radar bands, combined with the short revisiting intervals, will prove to be a formidable asset for disaster monitoring and damage assessment. This will particularly apply to natural disasters like earthquakes, floods and fires - with important contributions in the case of other meteorology-related disasters - as well as to disasters caused by man. The fully ground commandable, multispectral imager and the I.R. sensor will greatly contribute to the determination of pollutants, supported, for specific targets like oil spills, by the SAR sensor.

The I.R. camera and the VIS/NIR imager can provide a better insight into the status of the coasts. Combining the high geometrical resolution of the panchromatic sensor with the coarser resolution of the other sensors results in innovative added-value products. Certain

analysis bands have proven to be inadequate for distinguishing different crop types. The I.R. and VIS/NIR imager can dramatically improve the quality of the end user products .

The unique COSMO/SkyMed features can further enhance the growth of commercially exploitable services in several applications:

- civil protection
- transport
- geology
- tourism
- insurance
- hydrological resources.

Although designed to satisfy the needs for advanced management of Mediterranean basin resources, the COSMO/SkyMed system could well be exploited for similar applications in other areas. It is planned to establish a commercial network on a global basis, sharing with other regional partners the resources made available by the COSMO/SkyMed system.

Three optical satellites are equipped with the following main sensors:

- a high resolution panchromatic camera
- a coarse resolution multispectral imager
- a medium resolution infrared camera (I.R.)
- four SAR satellites equipped with an X-band (9.6 GHz) Synthetic Aperture Radar

A high data rate transmission facility, operating at X-band via mechanically re-pointable directive antennas, serves for direct transmission of the data generated by the high and medium resolution sensors. X-band Data Receiving stations are equipped with moderate size antennas, less than 3 m in diameter.

A low data rate S-band transponder via a wide beam antenna, is dedicated to several operations:

- retransmission of on-board stored data to small terminals
- gathering data transmitted from ground-based sensors
- implementing @-mail in a store-and-forward communication

The COSMO/SkyMed ground segment includes:

- Constellation management infrastructure (Mission Control Centres and Satellite Control Centres)
- Decentralized ground-based user facilities for direct data collection from the satellites
- Centralized archiving facility.

The management of the COSMO/SkyMed constellation will make use of multiple Satellite Control Centres linked to the Mission Control Centre in a star configuration.

A flexible and cost-effective solution implements the following features:

- reception of data directly from overpassing satellite via an X-band communication link for the high-speed data channel and/or via an S-band communication link for the low-speed data channel
- a "store-and-forward" data service in S-band, using the satellites of the constellation
- a standard data processing facility
- a special purpose data processing package
- interface with the Mission Control Centre for satellite resource allocation and planning
- interface with the archiving facilities.

Stations can be configured to be transportable to meet specific logistic requirements. Within the framework of the COSMO/SkyMed program it is planned to implement the National Data Receiving Processing and Centralized Archiving Centre(s) to serve, at regional level, the users not equipped with direct access to satellite data. Note that very few specifics were mentioned for COSMO/SkyMed science data processing.

Tsinghua Constellation

Surrey Satellite Technology Ltd (England), a University of Surrey company, and Tsinghua University (China) have formed a Collaborative Joint Venture company in Beijing to develop advanced microsattellites for China. A market for over 100 small satellites over the next 5-8 years has been identified within China and SSTL is the first foreign company to establish a joint venture in this market, accessing business worth some £300 million.

The 25-year joint venture company, to be known as the "Tsinghua-Surrey Small Satellite Company (T-SSSC)", is the result of more than five years extensive work by SSTL in China promoting the use and applications of sophisticated small satellites as a more rapid and lower cost approach to meeting China's space requirements. The formation of this first private satellite manufacturing company in China reflects the desire of the government to introduce increasing commercial market forces into the Chinese space industry.

"This is a world-first breakthrough for a British company into the closely-controlled Chinese satellite industry and we look forward to working with Tsinghua to develop small satellites for the Chinese market", said Professor Martin Sweeting, Director of the Surrey Space Centre and CEO of SSTL.

The first £3 million contract for T-SSSC has already been signed between Surrey and Tsinghua for a 50kg microsatellite (to be called Tsinghua-1) which will form the first demonstrator for a constellation of seven microsatellites to provide daily world-wide high resolution imaging for disaster monitoring and mitigation, planned for launch in 2000. The microsatellite will also carry out communications research in low Earth orbit at the end of 1999 after launch on a Chinese Long March rocket.

In September, 1998, the Surrey Space Centre and the Tsinghua Aerospace Centre also launched a joint "Tsinghua-Surrey Small Satellite Research Centre" which will specialize in advanced academic research and development of microsatellite and nanosatellite technologies.

No details were provided on the processing of the science data from the Tsinghua satellites.

Approaches

Based on an evaluation of the above-mentioned constellation projects, and noting the lack of hard requirements in any of these, the following approaches are suggested to meet the oncoming requirements for Science Data Processing of constellations of nanosats. In almost all cases, the constellation projects are vague in their requirements for data processing. This is most likely because they are making the assumption that legacy systems will scale to meet their requirements, without a significant increase in costs. It will become critical to become involved early in the planning and requirements phase of the constellation projects, to ensure that data processing requirements are being properly considered. The constellation projects seem to be focusing on the hard, up-front requirements for care and feeding of a hundred spacecraft, mission planning and re-planning, mission ops, orbit and attitude determination. The commercial projects, either because they return no science data, or because they are very early in their planning stages, have provided no guidance in the science data processing area.

1. Take advantage of advances in basis technology

Computers will become faster and cheaper into the foreseeable future. Processor speeds and memory densities have yet to hit a wall, and continue to follow Moore's law without a discernable leveling of the rate of technological advance. However, the mere increase in speed, memory, and I/O capacity will not suffice to contain costs for processing of science data for advanced constellation missions. It may be possible to process 5 or 10 times the amount of data that present-day missions produce, for the same or less cost. However, this process does not scale to 100's of data-returning spacecraft.

The impacts of processing larger numbers of spacecraft, and larger data sets, are not constellation-unique. We can expect increased workload in all these areas, constellations or not. The "March of Technology" will solve some of these problems. The cost of computing power and storage (even for on-orbit systems) is trending towards zero. Transmission costs are also trending to zero, albeit at a slower rate than processing power or storage costs. Alternatives such as Internet from commercial sector and growth of the ground-based optical infrastructure provide new lower cost options for moving data from sensor to end-user.

Alternates to CCSDS such as use of TCP/IP may eliminate or reduce need for LQP. This is the thrust of the end-to-end satellite networking concept. This should also serve to reduce life-cycle costs.

2. Take advantage of parallel processing approaches

Any given data processing architecture will have bottlenecks, because either the processor is waiting for the memory (processor stall), or the memory or I/O subsystem are waiting for the processor (I/O bound). Communications speed is limited by the minimum channel capacity in the system, and processing speed is limited by the slowest hardware element. Ideally, the computation rate should balance the I/O rate, but this is a

function of the problem domain, and the algorithm. Processing speed is increasing (and has historically) because of increasing clock rates, decreased feature size, and more advanced architectural techniques (superpipelining, superscalar, risc). This trend will continue into the near future, until fundamental physical barriers are met (speed of light, atomic feature size, quantum effects, etc). I/O capability has not scaled as well. Memory capacity has scaled, but still lags computational complexity.

As a general principle, the computation rate should balance the I/O rate. Consider a computational problem, for example, image texture analysis, that requires more resources than a single processor can provide. In adding a second or subsequent processors, we achieve diminishing returns in processing power, because we have created communication requirements between processors with bandlimited channels. Ahmdahl's Law says we get less than 1 unit of incremental processor power per added processor. In most real designs, the curve of incremental processor power per added processor displays a sharp fall-off. In a well-balanced system each added processor can add nearly a complete increment of processing power to the system. This is the limitation that parallel processing systems hit. This is an architectural issue, and each processing algorithm has inherent computational and I/O requirements, and associated bounds. Understanding these allows for the scaling of systems without wasting resources.

We need to examine the scalability of representative and legacy science data processing algorithms, to device systems that do scale properly across N datasets. In terms of ground-based processing, we can think of passing the various instrument datasets through the same pipeline, and posting in the same databases. The concept of object-orientation applies, where the top level object is the constellation, the next level down is the spacecraft, the next level is the instrument.

The processing of multiple datasets through the same pipeline requires us to determine the processing and I/O requirements of the pipeline implementation, and its scalability. First guess would be that the pipeline scales linearly in time - 10 datasets takes 10 times as long with the same hardware, or the same time, on hardware that is 10 times faster (in CPU and I/O capability). The example is the OPUS pipeline, developed for HST, used on FUSE, and being looked at for SWIFT. We have implemented this on a Linux box in the Code 586 lab.

The impact on science data processing is to determine the scalability of current science data processing systems, to determine if they are applicable to constellations. The fact that the instrument set is homogeneous in the near term helps. The issues are to examine the science data processing with respect to processing and I/O requirements. If the algorithms and processes are computationally limited, then faster or scaled underlying hardware is the answer. If the algorithms are more I/O bound, the situation is more complicated. I/O channel bandwidth does not scale as linearly as does computational horsepower.

3. Migrate some data processing onboard

There is the same trade-off with members of a constellation as with individual spacecraft on onboard versus ground based processing of science data. Migrating some of the processing of data onboard (where resources are more expensive) makes sense if downlink bandwidth/availability is a more costly resource. The problem comes more into focus when we are talking about a 100x problem.

We can investigate and advocate moving more of the routine science data processing onboard. This mitigates some of the downlink problem, and simplifies the ground based resources required. How do we avoid complicating the onboard problem? If portions of the science data processing can be instantiated in reconfigurable hardware onboard, the incremental costs are driven low. Reconfigurable hardware provides the economy of scale and speed of hardware, avoiding the lock-in problem by being changeable.

4. Develop more automated processing

The aggregate data volumes and rates issue is not constellation unique. We can safely predict that, constellations or not, science data processing will be faced with handling rapidly increasing data set sizes and rates. This forces the questions of scalability of communication, computation, and data storage resources.

For science data distribution, we must be concerned with data archiving, data security and privacy, timely data access - non of these are constellation-unique. We should continue to investigate methods of data dissemination - web-based is the technique du jour. Is this what the experimenters want? Are CD/DVD technologies applicable? Where are the bandwidth/storage trades in the system? How are these affected by the deployment of constellations?

Recommendations

1. Continue to collect and track requirements for constellation science data processing. As the constellation missions get closer to launch, their requirements will hopefully firm up. Try to get involved with the projects to drive the consideration of the science data processing tasks.
2. Continue to track the basis technology, that will give less than order-of-magnitude increases in processing power, memory capacity, and I/O bandwidth. This is the short term solution.
3. Continue to explore and prototype technologies for science data processing that will scale to hundred's of input sources. These may include the OPUS Science Data Pipeline from STScI. Hosted under Linux, it scales across multiple hosts with the Code-900 developed Beowulf technology. The major cost driver for processing will not be the installed cost of the systems, but in their operation. Automation of the processing is a must.

The following is from the Report of the NASA Magnetospheric Constellation Science and Technology Definition Team:

"It is widely recognized that the data sets generated by constellation missions require data management and handling techniques that are outside the current experience with space missions. Nevertheless, the problem is not qualitatively different from that associated with the conduct of atmospheric meteorology research and monitoring."

"The most fundamental problem is the visualization of both scalar and vector field information from a large number of observing stations. Some techniques developed for meteorology will be directly transferable to use with constellation data sets. Others will require new techniques, for example the visualization of magnetic field information that is not present in atmospheric meteorology."

"The next step beyond basic visualization is the assimilation of the data into global circulation models. This will allow for instantaneous comparison with such models, extrapolation of the observations into other parts of the system outside the constellation, and projection or forecasting of system behavior for comparison with actual observed system evolution. This is a complex process, which has been discussed in much more detail in the section on science objectives, above."

"Because the treatment of constellation data is so foreign to space physics, there is a significant need for the development of appropriate tools, borrowing wherever possible from prior work along the same lines that has already been completed in meteorology. As an integral part of the technology development effort for DRACO, developments along these lines should be supported at appropriate institutions with expertise in visualization and assimilation of data. Researchers who are active in the global simulation of magnetotail processes should undertake a significant amount of this work. They are in a position to generate simulated data sets, to introduce realistic errors in them, and then to develop the means to re-assimilate the simulated data back into the same model that generated it, or other independent models."

4. Continue to investigate migration of routine science data processing onboard the spacecrafts, either taking advantage of better onboard computing resources, or using reconfigurable computing/FPGA technologies.

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